Digital Elevation Model of Oahu, Hawaii:
Procedures, Data Sources and Analysis

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1. Introduction

In September of 2011, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed a bathymetric–topographic digital elevation model (DEM) of Oahu, Hawaii (Fig. 1). A 1/3 arc-second[1] DEM referenced to mean high water (MHW) was carefully developed and evaluated. The 1/3 arc-second MHW DEM will be used as input for the Method of Splitting Tsunami (MOST) model developed by the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation. The DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Figs. 2 and 3). The DEM will be used for tsunami inundation modeling, as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the Oahu DEM.

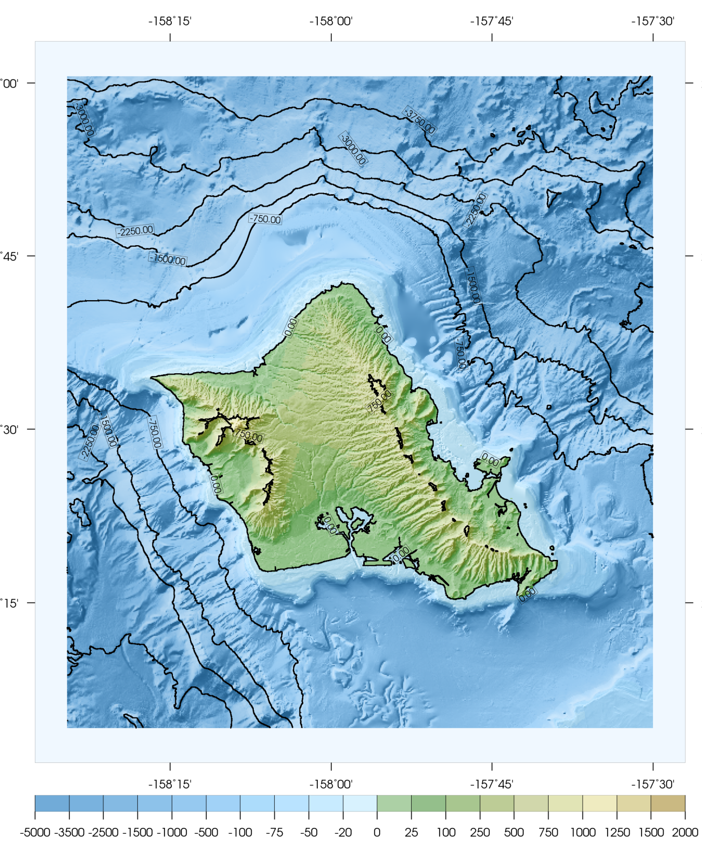

Figure 1. *Shaded relief image of the Oahu DEM.*

[1]The Oahu, HI DEM is built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Oahu, HI, 1/3 arc-second of latitude is equivalent to 10.256 meters; 1/3 arc-second of longitude equals 9.347 meters

2. STUDY AREA

The Oahu DEM covers the island of Oahu, Hawaii (Fig. 2). The DEM incorporates all Oahu communities such as the City of Honolulu, which is the largest settlement on the island of Oahu and in the State of Hawaii.

Table 1. Specifications for the Oahu DEM

Grid Area	Oahu, Hawaii
Coverage Area	-158.45 °, 22.06 °, -157.45 °, 21.02 °
Coordinate System	Geographic decimal degrees
Horizontal Datum	North American Datum of 1983 (NAD 83)
Vertical Datum	MHW
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ESRI Arc ASCII grid

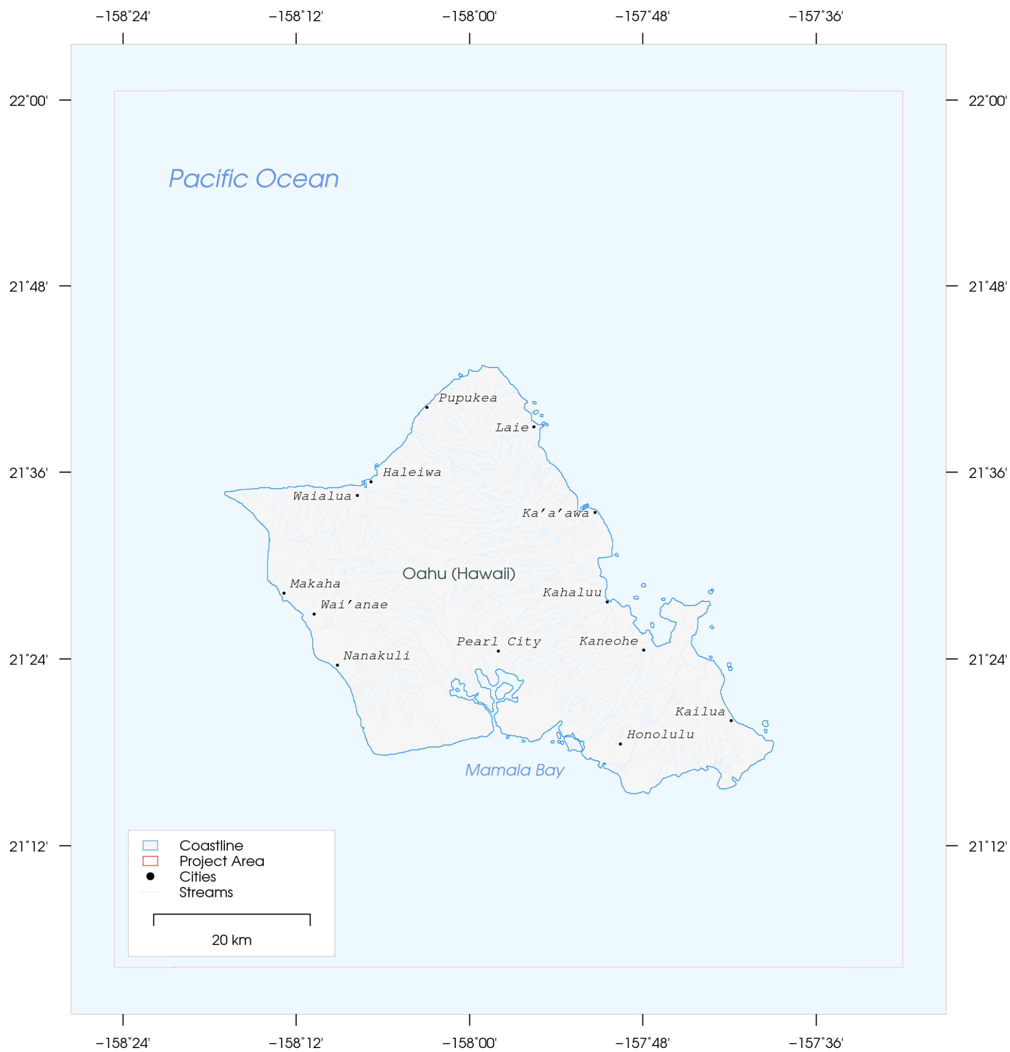

Figure 2. *Overview map illustrating the extents of the Oahu DEM*

3. SOURCE ELEVATION DATA

The best available digital data were obtained by NGDC from several U.S. federal agencies: NOAA's NGDC, Office of Coast Survey (OCS) and U.S. Army Corps of Engineers (USACE). Data were gathered in an area slightly larger (∼5%) than the DEM extents. This data 'buffer' ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

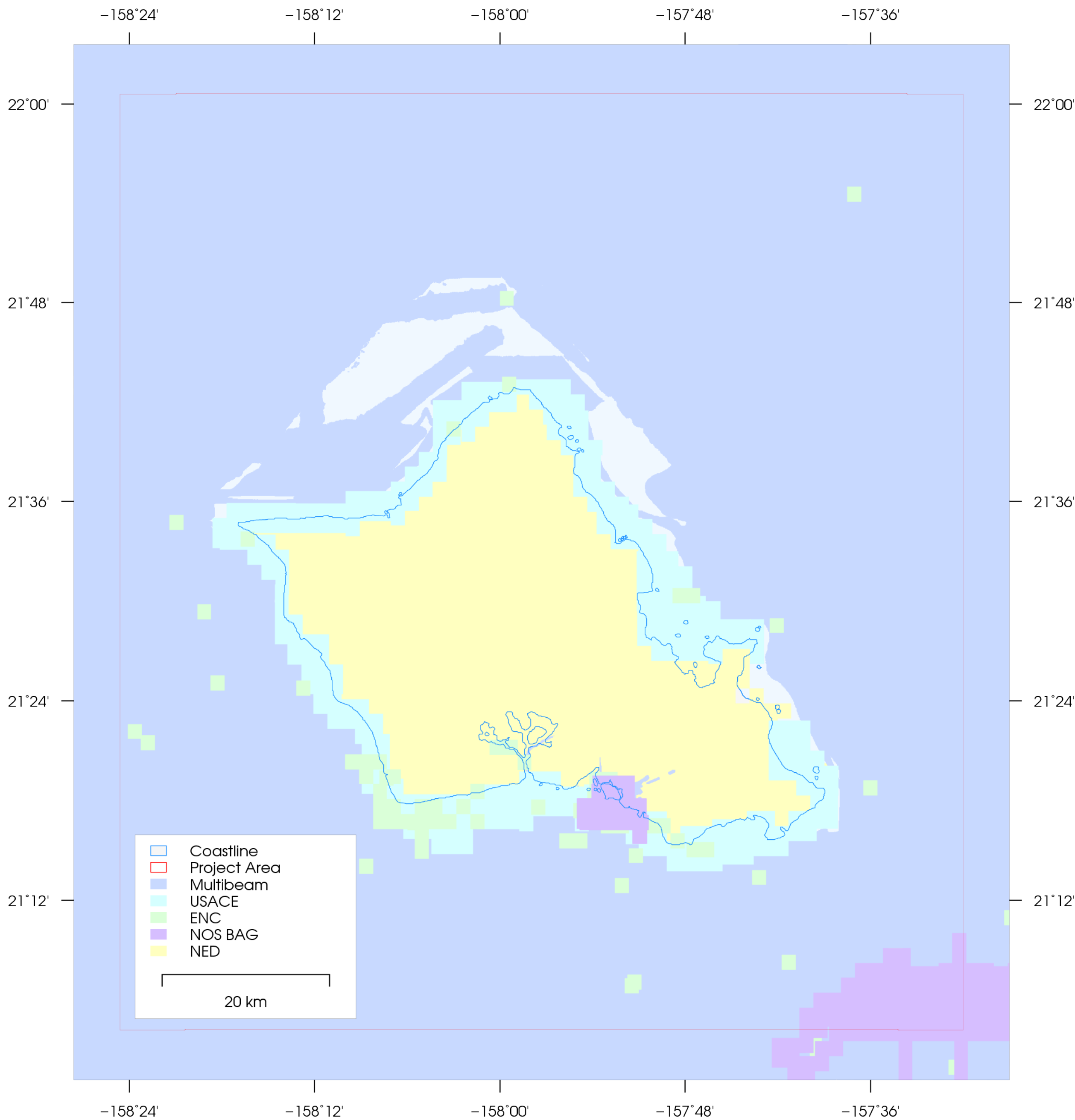

Figure 3. *Data sources in the Oahu region.*

3.1 Data Sources And Processing

Coastline, bathymetric, and topographic digital datasets (Tables 2, 3, 4 and 5; Fig. 3) were obtained by NGDC and shifted to common horizontal and vertical datums: NAD 83 geographic[2] and MHW, respectively. The datasets were assessed to determine data quality and were manually edited where needed. Vertical datum transformations to MHW were accomplished using a constant offset obtained from averaging the differences between datums at various tidal gauges around Oahu (Table 6, Fig. 4).

3.1.1 Coastline

Coastline datasets of the Oahu region were obtained from a variety of sources. The main dataset used in developing a combined, detailed coastline was the zero-line contour extracted from the coastal lidar and Interferometric Synthetic Aperture Radar (IfSAR) datasets (Table 2, Fig. 3). This dataset provided a detailed MHW coastline of the Oahu region. NGDC evaluated but did not use the NOAA Office of Coast Survey (OCS) coastline.

The zero-line contour coastline was edited by NGDC using ESRI World Imagery to better represent the coastline immediately sourrounding bays and inlets and to ensure the resolution of the breakwaters in the region, which were not adequately represented in other data sources.

Table 2. Shoreline datasets used in compiling the Oahu DEM

Source	***Year***	***Data Type***	***Spatial Resolution***	***Original Horizontal Datum/Coordinate System***	***Original Vertical Coordinate System***	***URL***
NGDC	2011	Composite vectorized hydraulic breaklines	Not defined	NAD 83 geographic	MHW	N/A
NGDC	2011	Digitized vector Coastline	Not defined	World Geodetic System (WGS) 84 geographic	MHW	N/A

[2] The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEM. Many GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant for our purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the waves passage across ocean basins. This DEM is identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geographic. At the scale of the DEM, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.

3.1.2 Bathymetry

Bathymetric datasets available in the Oahu region included 168 NGDC multibeam sonar surveys, three National Ocean Survey (NOS) high-resolution surveys in Bathymetric Attributed Grid (BAG) format, and 10 Electronic Nautical Charts (ENCs) that were available from OCS (Table 3; Fig. 3). NGDC evaluated but did not use the NOAA NOS hydrographic dataset due to conflicts with the multibeam surveys.

Table 3. Bathymetric datasets used in compiling the Oahu DEM

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Coordinate System*	*URL*
NGDC	2011	Multibeam soundings	N/A	NAD 83 geographic	Assumed mean sea level (MSL)	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
NOS BAG	2008–2009	Soundings	N/A	NAD 83 geographic	mean lower low water (MLLW)	N/A
OCS	2010	Extracted points from ENC	Ranges from 1:20,000 to 1:458,596 (varies by chart)	WGS84 geographic	MLLW	http://www.nauticalcharts.noaa.gov

1) NGDC Multibeam

One-hundred-sixty-eight multibeam swath sonar surveys were available from the NGDC multibeam database for use in the development of the Oahu DEM (Fig. 3). This database is comprised of the original swath sonar files of surveys conducted mostly by the U.S. academic fleet. All surveys have a horizontal datum of WGS 84 geographic and an undefined vertical datum, assumed to be equivalent to MSL. The data were gridded to 1 arc-second resolution using MB-System and xyz data were extracted and transformed to MHW using a constant offset.

2) OCS Electronic Navigational Charts

Ten ENC datasets were available from OCS in the Oahu coverage area (Fig. 3). The ENCs were downloaded from the OCS web site, and were horizontally referenced to NAD 83 geographic and vertically referenced to MLLW (meters). The data were transformed to MHW using a constant offset and were reviewed and compared to the coastline and to the corresponding RNCs.

3) NOS/BAG Hydrographic Surveys

A total of three NOS high-resolution hydrographic surveys, in BAG format, were conducted between 2008 and 2009 and were available for use in the development of the Oahu DEM (Fig. 3). The data were vertically referenced to MLLW and horizontally referenced to NAD 83 geographic.

3.1.3 Topography–Bathymetry

The topography–bathymetry dataset used to build the Oahu DEM include 29 high-resolution coastal lidar surveys from the USACE Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) Coastal Topography-Bathymetry Lidar; (Table 4; Fig. 3).

Table 4. Topography–Bathymetry dataset used in compiling the Oahu DEM

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Coordinate System*	*URL*
USACE	1999–2000	Bare-earth lidar	1 - 5 meters	WGS 84 geographic	MLLW	http://shoals.sam.usace.army.mil/Hawaii/pages/Hawaii_Data.htm

1) USACE SHOALS Coastal Topography–Bathymetry

Surveys of the Hawaiian Islands were conducted in the years 1999 and 2000. The islands of Kauai, Maui, and parts of Molokai and Oahu were surveyed in 1999. The survey conducted in 2000 included the islands of Hawaii, Maui, Molokai, Lanai, Oahu, and Kauai. The surveys were compiled for US Naval Oceanographic Office, U.S. Geological Service, and U.S. Army Corps of Engineers Honolulu District.

3.1.4 Topography

The topographic dataset used to build the Oahu DEM was the US Geological Society (USGS) National Elevation Dataset (NED) 1/3 arc-second DEM; (Table 5; Fig. 3).

Table 5. Topographic datasets used in compiling the Oahu DEM

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Coordinate System*	*URL*
USGS	2011	Bare-earth DEM	1 - 5 meters	WGS 84 geographic	NAVD88	N/A

1) **USGS NED 1/3 arc-second DEM** The USGS NED provides complete 1/3 arc-second coverage of the Hawaiian Islands. Data are in NAD 83 geographic coordinate and assumed MSL vertical datum (meters), and are available for download as raster DEMs. The bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov). The dataset was derived from USGS quadrange maps and aerial photographs based on topographic surveys; it has been revised using data collected in 1999. The NED DEMs were transformed to NAD 83 and MHW using a constant offset (Table 6). The gridded data were evaluated and positive elevations over open water were removed by clipping the data to the coastline using GDAL and Python. The resulting data were converted to xyz data using GDAL.

3.2 Establishing Common Datums

3.2.1 Vertical Datum Transformations

Datasets used in the compilation and evaluation of the Oahu DEM were originally referenced to MLLW or MSL. All datasets were transformed to MHW using constant offsets obtained from averaging the differences between datums at various tidal gauges around Oahu (Table 6; Fig. 4).

- **Bathymetric Data:** All hydrographic surveys were transformed from MLLW or MSL to MHW using a constant offset based on the relationships shown in Table 6.
- **Topographic–Bathymetric Data:** All topographic–bathymetric datasets used in the compilation of the Oahu DEM originated in MSL vertical datum and were transformed to MHW using a constant offset based on the tidal relationships shown in Table 6.
- **Topographic Data:** All topographic datasets used in the compilation of the Oahu DEM originated in MSL vertical datum and were transformed to MHW using a constant offset based on the tidal relationships shown in Table 6.

3.2.2 Horizontal Datum Transformations

Datasets used to build the Oahu DEM were downloaded or received referenced to WGS 84 geographic or NAD 83 geographic horizontal datums. The relationship transformational equations between these horizontal datums are well established. Data were transformed to a horizontal datum of NAD 83 geographic using *Proj4*.[3]

3.3 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the ascii *xyz* files were reviewed for consistency between datasets. Problems and errors were identified and resolved before proceeding with subsequent gridding steps.

[3]*Proj4* is a free standard Unix filter function which converts geographic longitude and latitude coordinates into cartesian coordinates, $(\lambda, \phi) \rightarrow (x, y)$, by means of a wide variety of cartographic projection functions. http://trac.osgeo.org/proj/

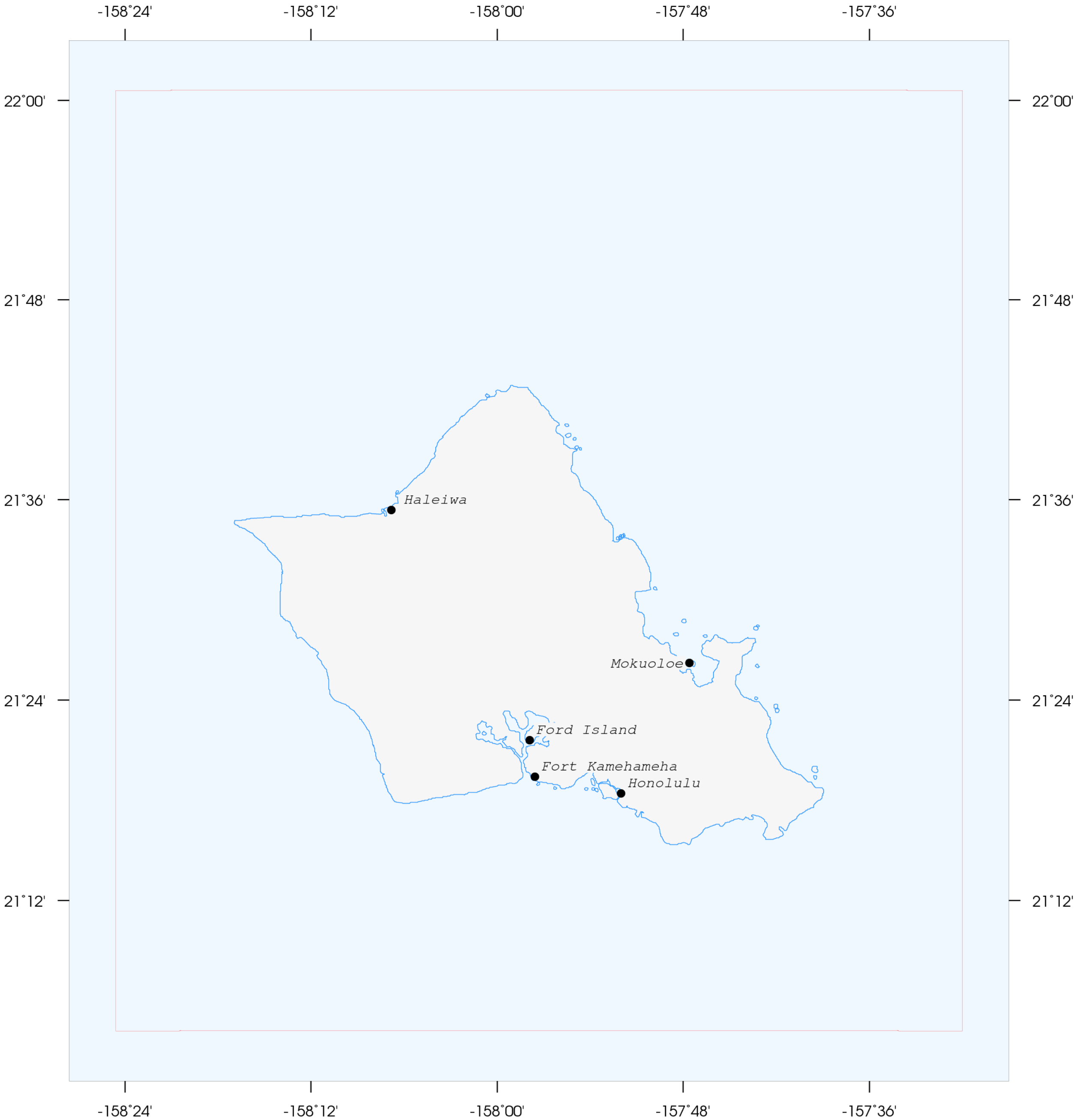

Figure 4. *Tide station locations in the Oahu region, Oahu project area shown in red.*

Table 6. Relationship between MHW and other vertical datums in the Oahu region

Station Name	***Difference to MHW (meters)***	
Oahu	MSL	-0.217
	MLLW	-0.499
Honolulu	MSL	-0.188
	MLLW	-0.439
Mokuoloe	MSL	-0.227
	MLLW	-0.547
Ford Island	MSL	-0.193
	MLLW	-0.454
Fort Kamehameha	MSL	-0.33
	MLLW	-0.581
Average	**MSL**	**-0.231**
	MLLW	**-0.504**

4. DEM Development

4.1 Smoothing of bathymetric data

The NGDC multibeam hydrographic survey data are generally sparse relative to the resolution of the 1/3 arc-second Oahu DEM. This is especially true for deep water surveys in the Pacific and shallow water surveys in bays where data have point spacing up to 350 meters apart. In order to reduce artifacts created in the DEM by the low-resolution bathymetric datasets, and to provide effective interpolation in the deep water and into the coastal zone, a 1/3 arc-second pre-surface bathymetric grid was generated using Generic Mapping Tools (*GMT*)[4]. The coastline elevation value was set at 0 meters to ensure a bathymetric surface below zero in areas where data are sparse or non-existent.

The point data were median-averaged using the *GMT* command "blockmedian" to create a 1/3 arc-second grid 0.05 degrees (∼5%) larger than the Oahu DEM gridding region. The *GMT* command 'surface' was then used to apply a tight spline tension to interpolate elevations for cells without data values. The *GMT* grid created by 'surface' was converted to an *ESRI* Arc ASCII grid file, and clipped to the final coastline (to eliminate data interpolation onto land areas) using *GDAL* and *Python*. The resulting surface was exported as an *xyz* file for use in the final gridding process (Table 7).

4.2 Building the MHW DEM

MB-System[5] was used to create the 1/3 arc-second Oahu DEM. The MB-System command 'mbgrid' was used to apply a tight spline tension to the *xyz* data, and interpolate values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 7. The resulting binary grid was converted to an Arc ASCII grid using the MB-System tool 'mbm_grd2arc' to create the final 1/3 arc-second Oahu DEM. Figure 5 illustrates cells in the DEM that have interpolated values versus data contributing to the cell value.

[4] *GMT* is an open source collection of ∼60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. *GMT* supports ∼30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. *GMT* is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. URL: http://gmt.soest.hawaii.edu/ [Extracted from *GMT* web site.]

[5] MB-System is an open source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars. The source code for MB-System is freely available (for free) by anonymous ftp (point and access through these web pages). A complete description is provided in web pages accessed through the web site. MB-System was originally developed at the Lamont-Doherty Earth Observatory of Columbia University (L-DEO) and is now a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and L-DEO. The National Science Foundation has provided the primary support for MB-System development since 1993. The Packard Foundation has provided significant support through MBARI since 1998. Additional support has derived from SeaBeam Instruments (1994–1997), NOAA (2002–2004), and others. URL: http://www.ldeo.columbia.edu/res/pi/MB-System/ [Extracted from MB-System web site.]

Table 7. Data hierarchy used to assign gridding weight in MB-System

Dataset	***Relative Gridding Weight***
IfSAR	100
USACE bathymetric-topographic lidar	75
NOS BAG	50
NGDC Multibeam	10
OCS ENC	10
Pre-surfaced bathymetric grid	1

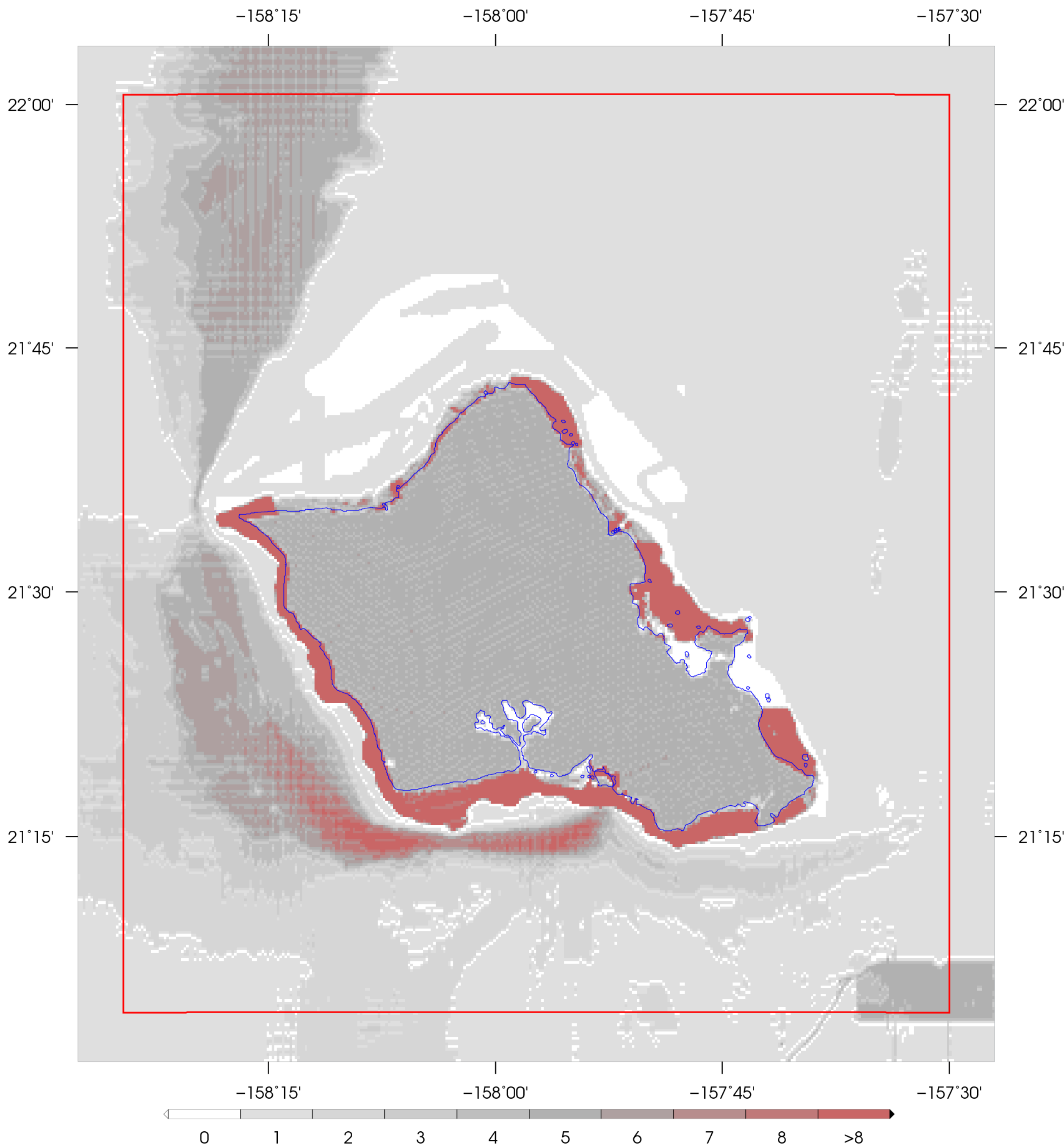

Figure 5. *Data density of the Oahu gridding region.*

4.3 Quality Assessment of the structured DEM

4.3.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Oahu DEM is dependent upon the datasets used to determine corresponding DEM cell values and the cell size of the DEM, making the highest accuracy possible 1/3 arc-seconds (about 10 meters). The horizontal accuracy is 10 meters where topographic IfSAR datasets contribute to the DEM cell value. The horizontal accuracy is 0.75 meters at 1 sigma where bathymetric–topographic lidar-derived data contributes to the DEM cell value. Bathymetric features are resolved only to within a few tens of meters in deep-water areas. Shallow, near-coastal regions, rivers, and harbor surveys have an accuracy approaching that of sub aerial topographic features. Positional accuracy is limited by: the sparseness of deep-water soundings; and by the morphologic change that occurs in this dynamic region.

4.3.2 Vertical accuracy

Vertical accuracy of the Oahu DEM is also highly dependent upon the source datasets contributing to DEM cell values. Topographic lidar has an estimated RMSE of 13.9 to 20 cm. Topographic IfSAR has an estimated RMSE of 2 meters or better in areas of unobstructed flat ground. Bathymetric-topographic lidar-derived data have a vertical accuracy of 0.20 meters at 1 sigma. Bathymetric areas have an estimated accuracy of between 0.1 meters and 5% of water depth.

4.3.3 Slope maps and 3D perspectives

GMT was used to generate a slope grid from the Oahu DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Figure 6). The DEM was transformed to projected coordinates (horizontal units in meters) using *GMT* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 7 shows a perspective view image of the 1/3 arc-second Oahu in its final version.

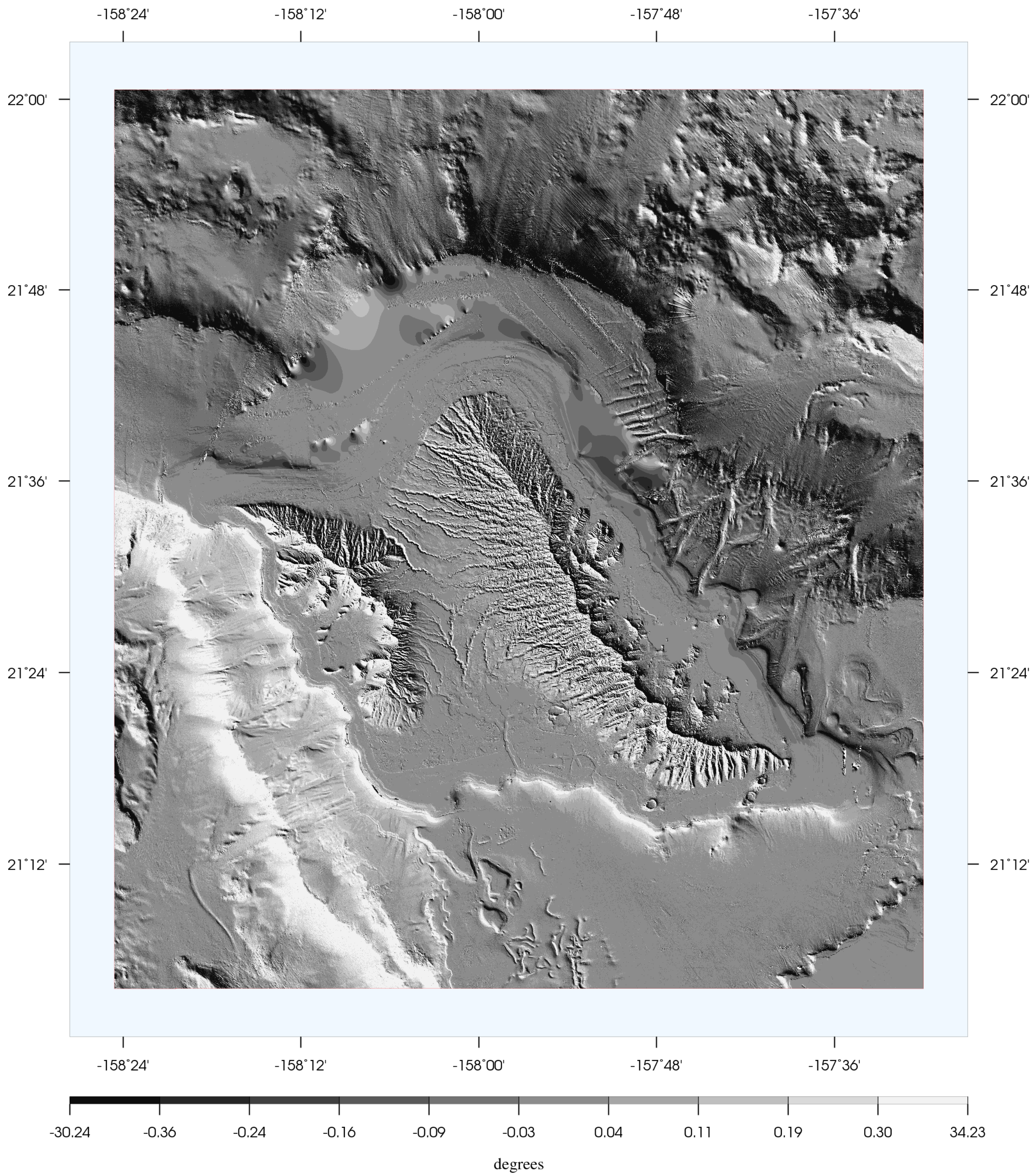

Figure 6. *Slope map of the Oahu DEM*

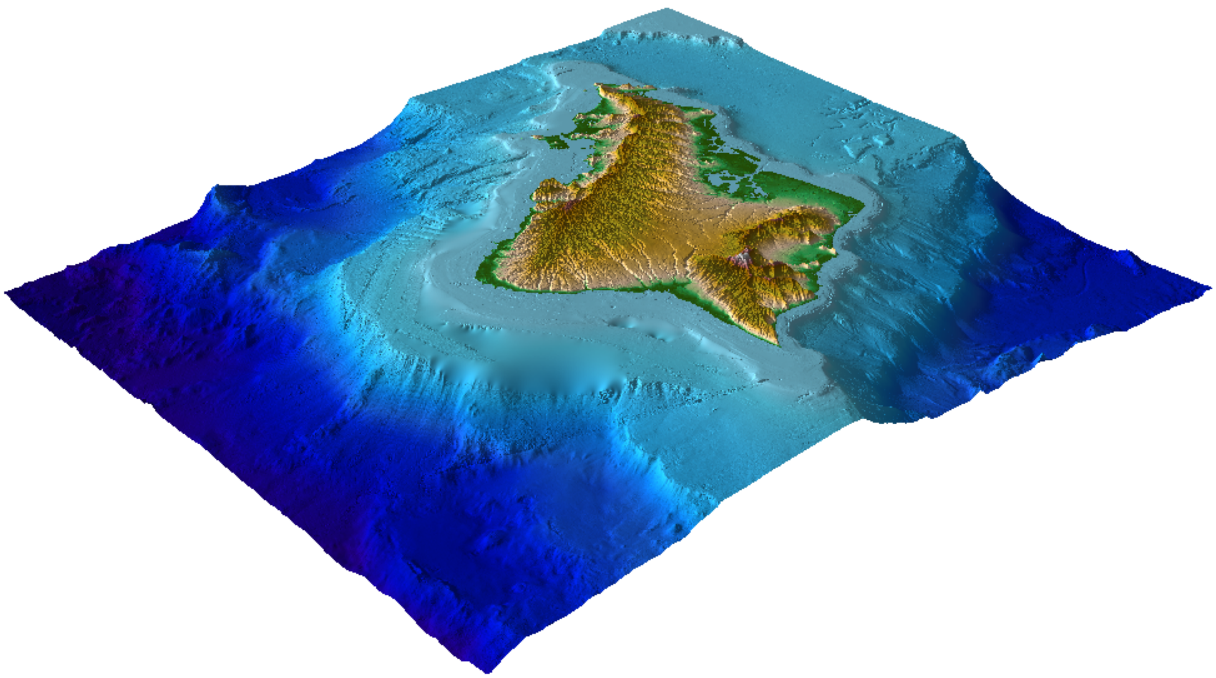

Figure 7. *Perspective view from the northwest of the Oahu DEM.*

4.3.4 Comparison with NGS geodetic monuments

The elevations of 1024 NOAA National Geodetic Survey (NGS) geodetic monuments (Figure 9) were extracted from online shapefiles of NGS geodetic monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give monument positions in NAD 83 geographic (typically sub-mm accuracy) and elevations in North American Vertical Datum (NAVD) 88 (assumed MSL). Monument elevations were transformed to MHW using a constant offset and were compared with elevations in the Oahu DEM. Differences between the DEM elevations and the NGS geodetic monument elevations range from -19.73 to 17.2938 meters, with the majority of them being within +/-1 meter (Figure 8). Negative values indicate that the monument elevation is less than the DEM elevation. After examination, it was determined that those monuments with the largest deviations do not represent ground surface as they are located on top of an observation tower, light house or at the apex of other structures.

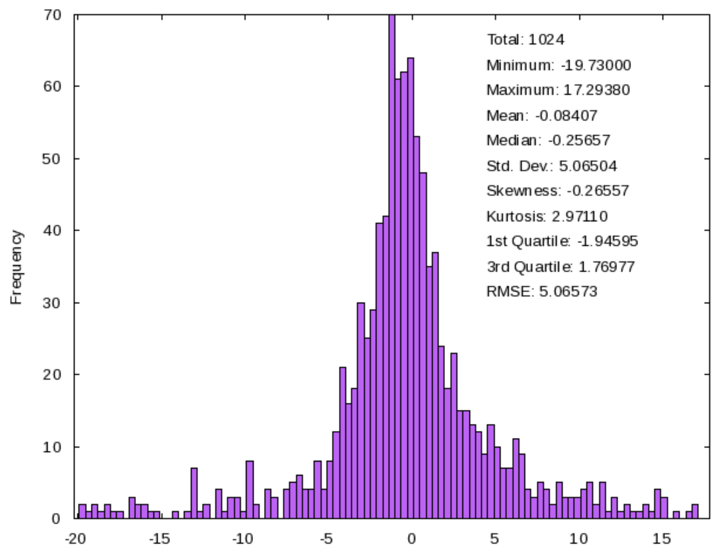

Figure 8. *Histogram of the differences between the NGS monument elevation values and the Oahu DEM*

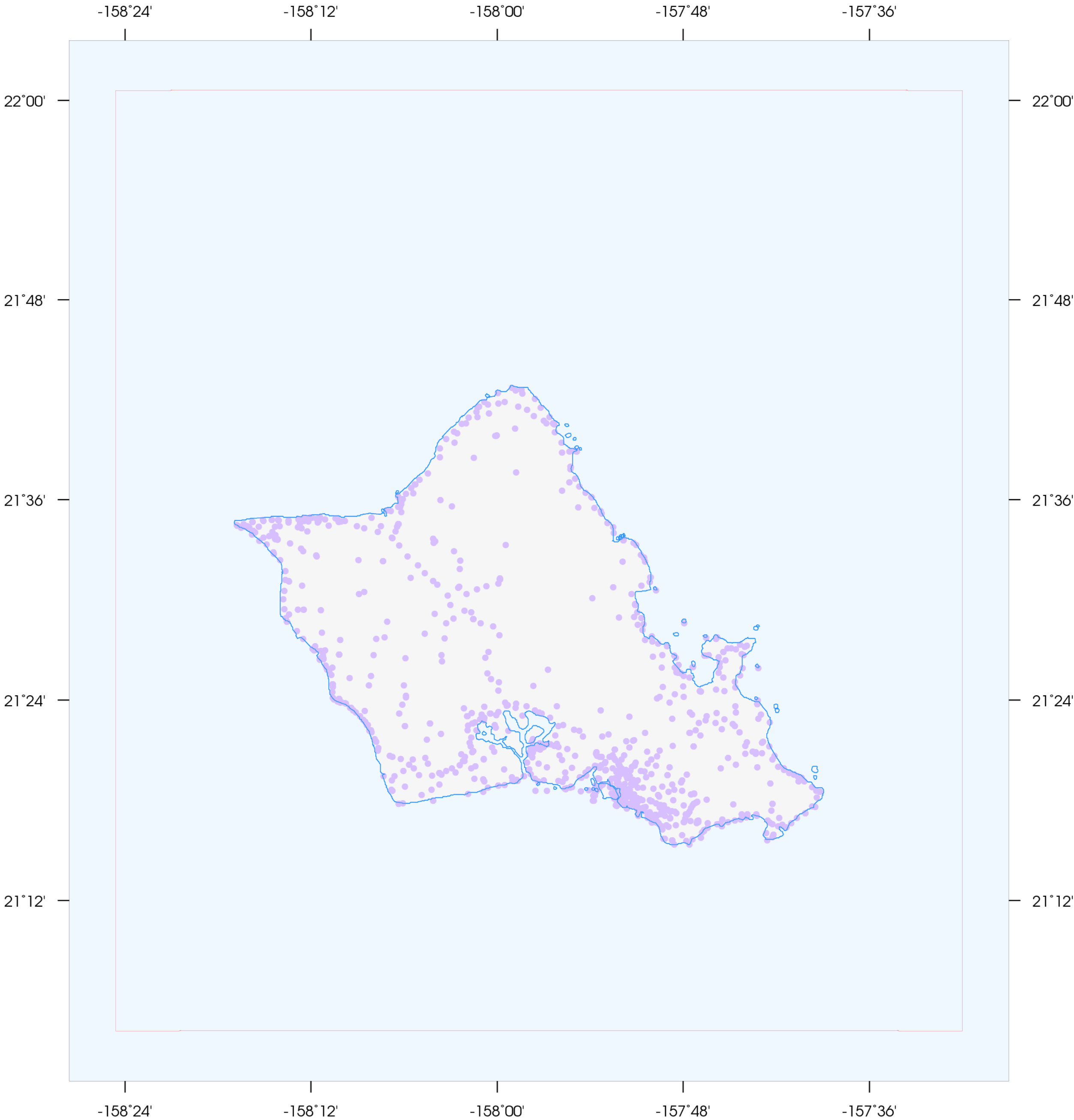

Figure 9. *Locations of NGS monuments used in the evaluation of the Oahu DEM.*

5. Summary and Conclusions

A bathymetric–topographic structured digital elevation model of the Oahu, HI region, with cell spacing of 1/3 arc-second, and a vertical datum of MHW was developed by NGDC for PMEL for use in tsunami generation, propogation and inundation simulations.

Recommendations to improve the Oahu DEM, based on NGDC's research and analysis, are listed below:

- Conduct publically available lidar surveys of all topographic regions.
- Conduct publically available high-resolution surveys of all harbors and bays.

6. Acknowledgements

The creation of the Oahu DEM was funded by NOAA PMEL. The authors thank Nazila Merati, Marie Eble and Vasily Titov (PMEL).

7. References

Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix A, 2003. Federal Emergency Management Agency, Flood Hazard Mapping Program.

8. Data Processing Software

ArcGIS 10, developed and liscensed by ESRI, Redlands, California, http://www.esri.com

ESRI World Imagery - ESRI ArcGIS Resource Centers, http://www.esri.com

GEODAS v. 5 - Geophysical Data System, free software developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas

GMT v. 4.1.4 - Generic Mapping Tools, free software developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu

MB-System v. 5.1.0, free software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System

Quick Terrain Modeler v. 6.0.1, lidar processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com

GDAL v. 1.8.0 Geographic Data Abstraction Library is a translator library maintained by Frank Warmerdam, http://gdal.org

Proj4 v. 4.7.0 free software developed by Gerald Evenden and maintained by Frank Warmerdam, http://trac.osgeo.org/proj/

VDatum v. 2.3 developed and maintained by NOAAs National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS), http://vdatum.noaa.gov/

A. SOURCE BATHYMETRY DATA